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Practical method to estimate energy potential generated by photovoltaic cells: practice case at Merida City

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Abstract

Nowadays, the use of renewable energy continues growing, particularly the solar photovoltaic, due to photovoltaic cells cost reduction and the grid connection ability, however a major challenge to encourage their use, is to rely on a method to estimate the potential energy generated by solar cells at specific location, it is important to sustain its viability or estimate generation projects in large and small scale. The photovoltaic cell conversion efficiency (η) and the maximum power point generated (P_{mpp}), is reduced by radiation (E) and temperature (T) variation, affecting the output current (I_o) and output voltage (V_o) respectively. This paper presents a practical method to calculate the energy generated per unit area based on cell mathematical model (P-N junction), the V-I and P-I characteristic curves, solar cell manufacturer data sheet, and a specific location climate database. This method provides the energy generated (kWhr) per square meter, per year, and the photovoltaic cell real conversion efficiency. A practice case at Merida City, México, is presented to expose the application method, for a five different 110W photovoltaic panel. As a result, the real conversion efficiency is lower almost 50% than conversion efficiency under standard test conditions ($T=25^{o}C$, $E=1000W/m^2$).

Keywords: Photovoltaic cell, solar energy potential, practice method.

1. Introduction

According to the World Energy Outlook 2012, the global electricity demand increases almost two times faster than energy consumption, a serious problem due to the necessary investment to replace obsolete infrastructure in the electricity sector [1]. The constant increase of the electricity demand has been mostly covered with oil, while the remaining is covered by natural gas and others like renewable energy.

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The renewable energy sources have the potential to generate clean energy available in nature, reduce the supply demand problem, solve the exhaustion of fossil fuels and mitigate the emission of greenhouse gases [2].The renewable energy with the higher capacity of installed power generation is the hydraulic and wind, which overcome the solar, however this latter is growing faster than any other renewable energy. Solar energy is available anywhere in the world, is considered inexhaustible and has a higher potential higher than annual generation of electricity worldwide. The solar energy potential is exploited through thermal and photovoltaic systems to generate electricity for a large scale like a central or small scale in autonomous systems or grid connected systems [3].

Nowadays, photovoltaic (PV) systems begin to penetrate the global market opportunities for micro power generation, through the opening of regulations, standards, and policies worldwide, the increase in the efficiency of solar energy conversion and the great reduction in costs per kilowatt installed [4]. However photovoltaic technology still has important challenges, one of them is the perception as an energy source with a prolonged investment return and unreliable. This is caused by the uncertainty in the potential of electricity generation, due to the natural variation of solar radiation between one area to another, as well as daily changes in climatic factors for a specific location where the PV panel is installed.

One of the determining factors for investing in photovoltaic generation is having a potential estimation and planning of electric power generation from solar energy available. Therefore it is necessary to have a practical method to estimate this potential for a specific location. Due to the high cost associated with the measurement instruments for solar radiation, several methods have been proposed to estimate the potential energy (kW/m^2) for a specific location, based in the solar radiation data as the Hotel's model to estimate direct radiation [5] and the Liu-Jordan's model to estimate diffuse radiation [6], in lately in the literature, several theoretical model for estimate the potential of solar electricity have been proposed [7, 8]. The previous proposed methods, estimate the potential of solar radiant energy for a specific location using climatic data, but don't estimate the power generation potential of the photovoltaic system. In practice, the difference between the available energy radiation referred to the electric generation potential of the cell, is significant. The generation potential of the photovoltaic system is affected by solar radiation (E), the temperature of the cell in the PN junction (T_{JP-N}), hours of sun exposure (Hr_{day}), the partial shading, the cell conversion efficiency (η) and operation at maximum power point (P_{mpp}) [9]. The last two factors depend on the cell intrinsic characteristics, so there are differences between a cell and another, as well as between manufacturers. The aim of this paper is provide a simple method for estimating electricity generation potential.

2. Development and methodology

2.1 Description of the method

The proposed method flowchart to estimate the potential power generation is presented in figure 1.

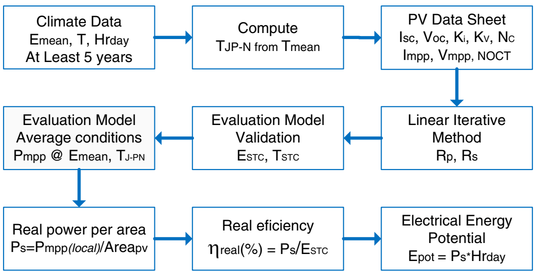

Fig. 1. Proposed method flowchart

The method consists of nine steps and is based on: the historical information from a climate database corresponding to one geographic location; the parameters from data sheet PV panel manufacturers, used to graph V-I and V-P characteristic curve; the application of any arithmetic method reported, to compute the R_s and R_b; the use of any mathematical evaluation model of PV cell, reported in the literature; some arithmetic calculations.

2.2. Climate data

The solar cells are sensitive to temperature variations affecting primarily the output voltage of the PV panel, and sensitive to radiation variations primarily affecting the output current, because these values constantly. A reliable climate database with at least five years was required, as the first step of this method, to compute the daily average of: radiation (E_{mean}), temperature (T_{mean}), and hours of insolation (Hr_{day}), along the years, for a specified location.

There are several databases available at worldwide as NASA Langley Atmospheric Sciences Data Research Center (LaRC), which provides historical data of 22 years for any quadrant of the globe defined by a Longitude and Latitude [10], another important database, is the European Solar Radiation Atlas (ESRA) [11]. Almost all countries have climate database of their geographic location, Mexico's National Water Commission (CONAGUA) has records for over 50 years [12]. Even within countries, locally or statewide, several educational institutions or government agencies keep records of temperature, insolation and radiation as the Center of Advanced Research (CINVESTAV) in Merida Yucatan Mexico [13]. In order to focus the aim of this paper, Merida City has been used as a study case.

2.3 PN junction temperature

The temperature effects on PV cell performance are mainly reflected in voltage output but also on the current and power output modifying their efficiency [14]. To measure the temperature junction ($T_{JP\text{-}N}$) of PV module, is complex because it is influenced by several parameters such as, ambient temperature, insolation, wind speed and direction, the irradiation spectral distribution, the absorption and heat dissipation capability, the PV module intrinsic materials, among the main ones[15].

Several papers have proposed methods and procedures to determinate the module junction temperature coefficient [16] referred on short current (I_{sc}) and open voltage (V_{oc}) of PV panel. A widely used method for estimating the junction temperature is presented by Alonso Garcia, through calculations based on the Nominal Operation Cell Temperature (*NOCT*) in compliance with international standards (EN-61646, EN-61215, E1036M) for polycrystalline, monocrystalline and thin film modules and arrays [17]. The procedure for determining the *NOCT* is based on the fact that the difference between the ambient temperature (T) and the junction temperature of the PV cell ($T_{JP\text{-}N}$) it has an independent behavior from ambient temperature but it has a proportional directly relationship to the radiation (E) for values above the 400W/m2. This allows determining the junction temperature from these parameters as follows:

$$T_{jP-N} = T_{mean} + (NOCT - 20)\frac{E_{mean}}{800} \tag{1}$$

The *NOCT* parameter has been obtained from data sheet PV panel manufacturer therefore it can be used to estimate de junction temperature cell applying equation 1 and substituting the values obtained from the climate database.

2.4 Data sheet parameters

The PV module intrinsic characteristics, determines its behavior, affecting the conversion efficiency of radiant energy into electrical energy. Therefore, it is important obtain from data sheet the following parameters: short circuit current (I_{sc}), open circuit voltage (V_{oc}), the temperature coefficient for I_{sc} (K_i), the temperature coefficient for V_{oc} (K_v), the number of cells connected in the panel (N_c), the current at the maximum power point (I_{mpp}) and the voltage at the maximum power point (V_{mpp}).

2.5 Mathematical model of PV cell

In order to determine the maximum power point (P_{mpp}) that can deliver a photovoltaic panel under certain condition junction temperature ($T_{JP\text{-}N}$) and radiation (E) it requires a mathematical model that allows approximating the nonlinear behavior PV panel through VI and VP curves.

The simplest model consists of a diode in parallel with a current source [19, 20], where the current source represents the radiation (E) and the diode represents the P-N junction PV cell.

An improved version adds the effect of series resistance (R_s) to enhance accuracy, but exhibited deficiencies with high values of junction temperature [21, 22]. Later was proposed add the effect of parallel resistance (R_p) with the diode and the current source to improve the behavior of the model [23, 24]. In resent dates is presented a model that added a second diode in parallel, as result it has significant improving accuracy without losing the simplicity, and includes partial shading capability [25].

2.5.1 Calculation of the series and parallel resistance

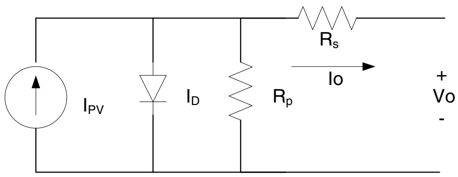

Fig. 4. PV cell model

Through equivalent model widely used for a PV cell with a diode, series and parallel resistor, as shown in Figure 3, the following equations are derived from an analysis of nodes.

$$I_o = I_{PV} - I_D - I_{Rp} \tag{2}$$

Replacing the current diode (I_D) by its characteristic equation and substituting the current resistance (IR_p) in terms of the output voltage (V_o), the output current (I_o) equation can rewrite as:

$$I_o = I_{PV} - I_{SAT}\left[exp\,\frac{q(V_o+I_oR_S)}{KT_c} - 1\right] - \frac{V_o+I_oR_S}{R_p} \tag{3}$$

To get the value of R_p at maximum power point (P_{mpp}) it is necessary replace the output voltage (V_o) by V_{mpp} and the output current (I_o) by I_{mpp}, given by the manufacturers datasheet. The equation that describes R_p is given by:

$$R_p = \frac{V_{mpp}+I_{mpp}R_S}{I_{PV}-I_{SAT}\left[exp\frac{q(V_{mpp}+I_{mpp}R_S)}{KT_c} - 1\right] - I_{mpp}} \tag{4}$$

According to the proposed method of Kashif Ishaque, for a finite value of R_s, the value of R_p has been obtained through iterative linear calculations of R_s values to approximate the maximum power point (P_{mpp}) [25]. Applying these equations in Matlab using five different PV panels, the mathematic method to obtain the value of R_s and $R_{p.}$ has been proved [26, 27, 28]. As a result, the figure 2 shows the iterative calculations of R_s and R_p closer to $P_{mpp,}$ at characteristic curves for one PV panel, the YL110Wp [18].

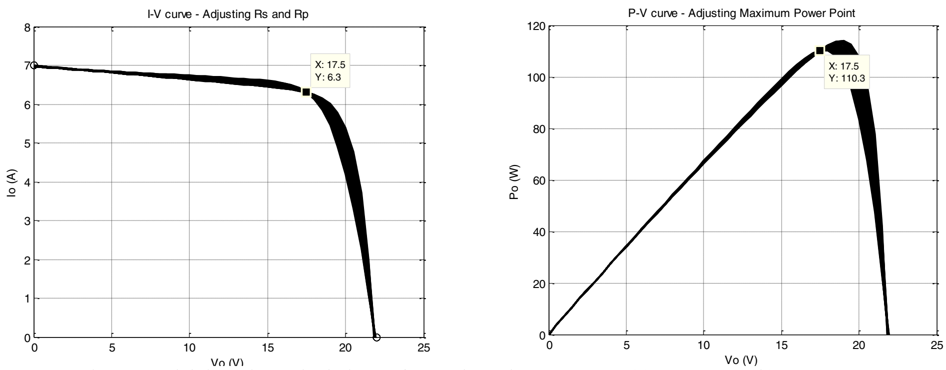

Fig. 2. Matlab iterative calculations of R_s and R_p closer to P_{mpp} : (a) V-I curve; (b) V-P curve

2.5.2 V-P and V-I characteristic curve matching

In order to prove the mathematical model of PV cell, each characteristic curves V-I and V-P simulated with Matlab has been matched with the five test subject panel datasheet. The equation 2 has been described in terms of the temperature and the radiation. The I_{PV} equation represents current from incident radiation and has been rewritten in term of average radiation (E_{mean}) and the average temperature (T_{mean}) as follows:

$$I_{PV} = I_E + [K_i * (T_{mean} - 25)] \frac{E_{mean}}{1000} \quad (5)$$

The diode current (I_D) has been described in terms of the average temperature (T_{mean}) as a function of the reverse saturation current by equation 6:

$$I_D = I_{SAT}\left[exp\frac{qV_D}{KT_c} - 1\right] \qquad I_{SAT} = \frac{I_E+[K_i*(T_{mean}-25)}{exp\left[\frac{q(V_{OC}+[K_V*(T_{mean}-25)]}{N_C*K*T_{jP-N}}\right]-1} \quad (6)$$

Substituting the values extracted from the PV manufacturer's data sheet and using the values of R_p, R_s and T_{JP-N} previously computed, as well as replacing the value of temperature and radiation with standard conditions test (*STC*), has been calculated the maximum power point (P_{mpp}) using the equations in Matlab proposed by Kashif Ishaque [29]. The mathematical model and the results of the V-I and V-P characteristic curves have been matched through Matlab simulation for different temperature and radiation versus each datasheets. Figure 3 shows one of the five results for the YL110Wp PV panel.

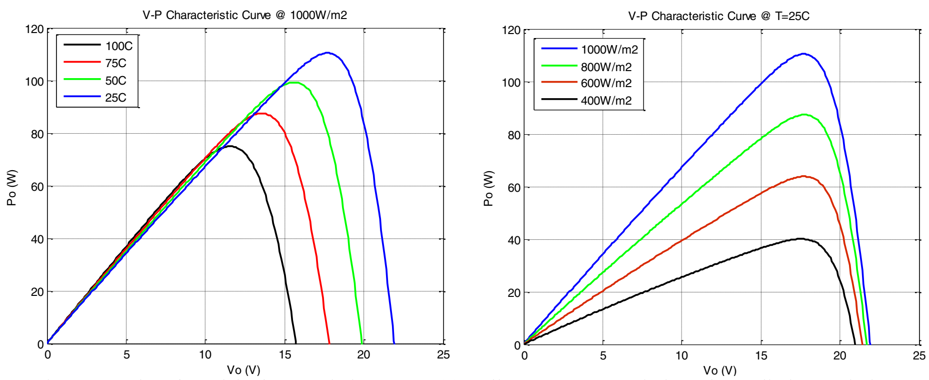

Fig. 3. Results of Matlab characteristic curves: (a) Cell temperature variation; (b) Radiation variation

2.6 Determining power generation (W)

After the mathematical model has been matched for each five PV panels datasheets, the maximum power point (P_{mpp}) at standards test condition (STC) has been computed applying the same Ishaque's model and has been necessary modifying Matlab developed equations in order to obtain in the same plot the new maximum power point for a daily average of temperature (T_{mean}) and radiation (E_{mean}) from a specific location. The difference between them has been was graphed and the power generation in Watts for specific location has been computed for five different 110W PV panel manufacturers to ensure the behavior mathematical model. The power generation for the YL110Wp PV panel was graphed in figure 4.

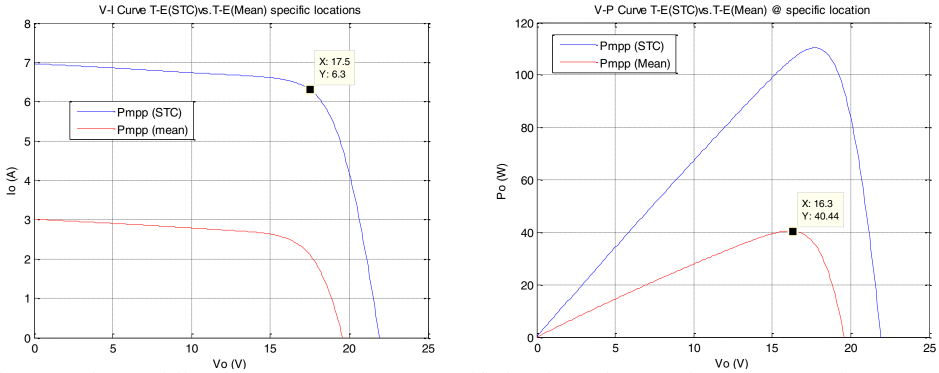

Fig. 4. Result P_{mpp} (daily average) vs. P_{mpp} (STC) at specific location and PV panel: (a) V-I Curve; (b) V-P Curve

2.7 Power per unit area (W/m^2)

The daily average of power per unit area (P_s) in W/m^2, has been obtained applying the equation 8 where the new maximum power point (P_{mpp}) for the specific location was computed by evaluation model in Matlab, and after was divided with the PV panel occupied area. This data has been provided by the manufacturer's data sheet. In equation form:

$$P_s = \frac{P_{mpp(location)}}{Area_{PV}} \tag{8}$$

2.8 Real energy conversion efficiency

The conversion efficiency by standard condition test was provided in manufacturer data sheet and is described in equation 9; however the real conversion efficiency for a specific location had differences. The PV panel real energy conversion efficiency (η_{REAL}) has been computed using the daily average of power generated (P_s) described in equation 8 versus standard irradiation (E_{STC}) obtained from climate database. The real energy conversion efficiency (η_{REAL}) has been described in equation 9 and has difference with the standard conversion efficiency (η_{STC}).

$$\eta_{\mathrm{STC}} = \frac{(P_{mpp(STC)}/PVarea)}{E_{STC}} \qquad \eta_{\mathrm{REAL}} = \frac{P_S}{E_{STC}} \tag{9}$$

2.9 Potential generation of electricity energy

The potential generation of electricity energy has been calculated multiplying the daily average of power generated (P_s) by the daily average of hours with sunlight (insolation). The daily average of insolation has been extracted from climate database for a specific location. The potential energy has been described by equation 10:

$$E_{pot} = P_s * Hr_{day} \tag{10}$$

3. Results

The Merida city as a specific location has been proposed for practical case and the CINVESTAV database has been used to extract the temperature, radiation and insolation parameters.

3.1 Daily average temperature, irradiation and daylight hours

In the next paragraphs the daily average for month of climate data was used in order to represent the difference between them along the year and look the variation according to location, so is possible to compute de potential of generation per month o year. In this paper the daily average annual has been computed by the arithmetic mean of the monthly values. The climate data average for each day has been averaged per month and then averaged for the same month of different years.

The daily average temperature for the months of at least five years records in Merida city has been presented in figure 5(a). The value of daily average annual from NASA, CONAGUA and CINVESTAV database has been shown in Figure 5(b). The NASA and CONAGUA daily average temperature includes day and night records, therefore using the CINVESTAV database has been obtained the daily average value only by daylight in order to closer to reality. Using available records of the last five years from CINVESTAV climatic database, the daily average temperature (26.45°C) has been computed, which was very close to NASA (26.4°C) and CONAGUA (26.2°C) records, allowing validate this database to use in this work. Filtering database only by daylight, the daily average temperature value, increases to 28.3°C. This value has been used as T_{mean}.

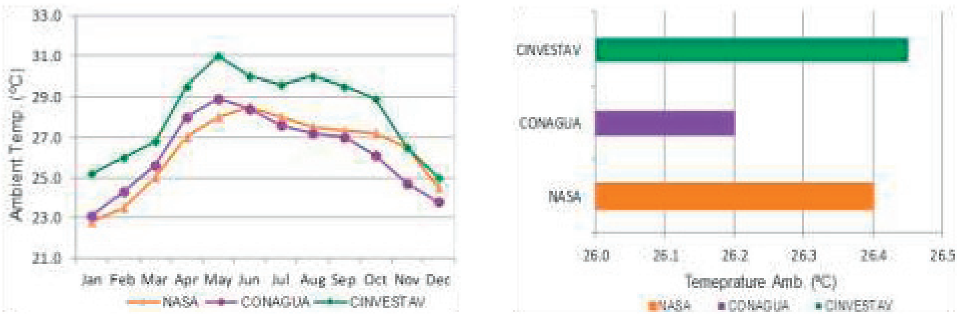

Fig. 5. (a) Temperature daily average monthly; (b) Temperature daily average annual

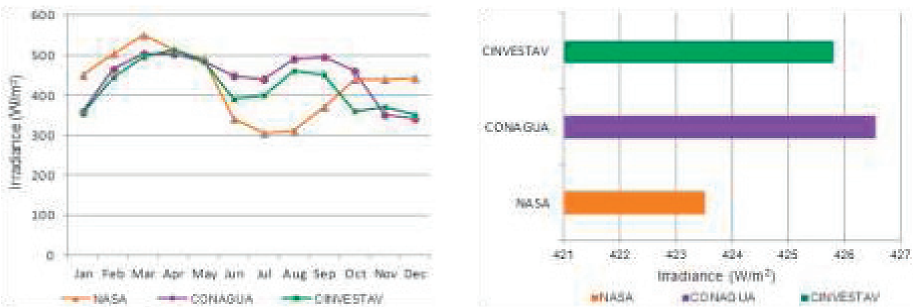

Fig. 6. (a) Radiation daily average monthly; (b) Radiation daily average annual

The daily average radiation for months of at least five years in Merida city has been graphed in figure 6(a). Applying the arithmetic mean of the radiation monthly values has been obtained the daily average per year. The value of daily average radiation for NASA (423.49W/m^2), CONAGUA (426.54W/m^2), and CINVESTAV (425.78 W/m^2) has been presented in figure 6 (b). The last value has been used as E_{mean}.

Applying the same method, the daylight hours has been extracted from climate database. The daily average daylight hours in Merida City was 12.17 hr. and has been presented in figure 7.

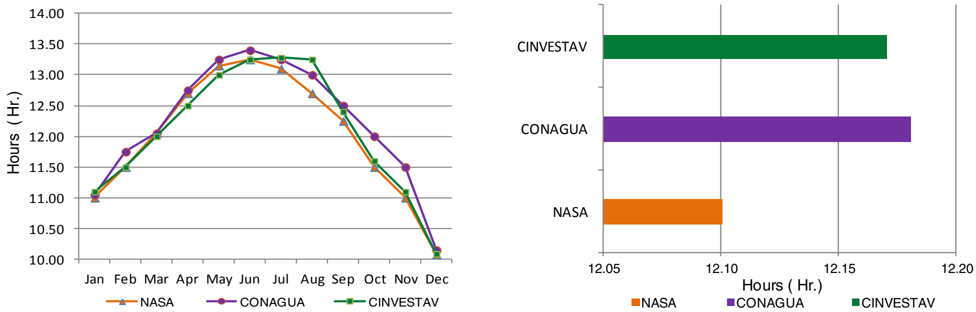

Fig. 7. (a) Daylight hours average monthly; (b) Daylight hours average annual

3.2 Potential energy generated in Merida city

Five different 110 Watts PV panel manufacturers datasheet has been used to prove the method proposed to estimate potential energy generated in Merida city. Applying the equation 1 to obtain the junction temperature cell, extracting the parameters from datasheets, and computing the R_s and R_p value the follow table has been integrated.

Table 1. Computed parameters to estimate the energy potential for different PV panels in Merida city

Manufacturer	Model	*NOCT*	$T_{jN\text{-}P}$	R_p	R_s	V_{mpp}	I_{mpp}	V_{oc}	I_{sc}	K_i	K_v	N_c
Yingli Solar	YL110Wp	46	42.13	43.76	0.23	17.5	6.30	22.0	7.00	0.0070	-0.081	36
Blue Carbon	BCT110-12	47	42.67	50.33	0.23	17.2	6.40	21.6	7.08	0.0046	-0.080	36
Mitsubishi	MF110EC4	45	41.60	41.14	0.17	17.1	6.43	21.2	7.16	0.0040	-0.073	36
Shell	SM110-12P	45	41.60	52.29	0.18	17.5	6.28	21.7	6.90	0.0028	-0.076	36
SolarTech	SPM110P	48	43.20	60.73	0.22	17.0	6.50	21.4	7.10	0.0035	-0.077	36

The evaluation model improved has been used to compute and plot in Matlab the relationship between the maximum power point at T_{STC} (25°C) and E_{STC} (1000W/m^2) versus daily average climate parameters from Merida city databases. The characteristic curve for each PV modules has been shown in figure 8.

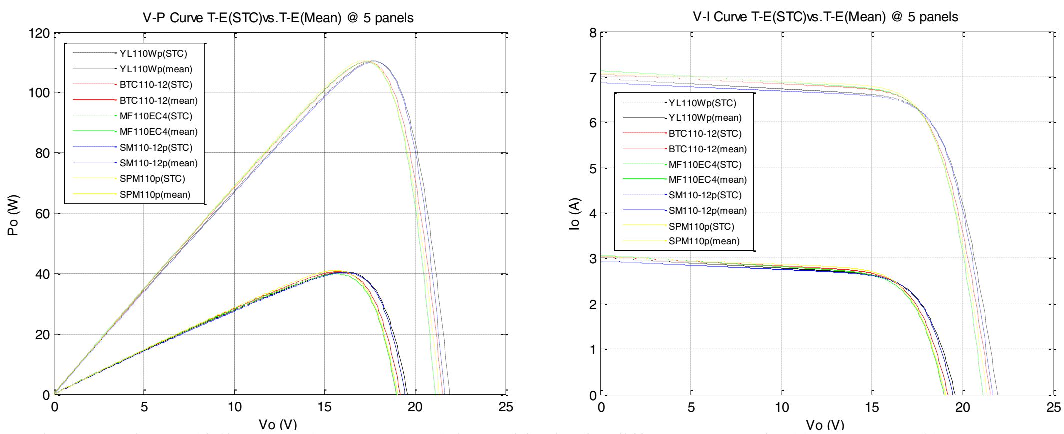

Fig. 8. Result P_{mpp} (daily average) vs. P_{mpp} (STC) in Merida city for different PV panels: (a) V-I Curve; (b) V-P Curve

The real and standard efficiency conversion, the standard and daily average power generated per unit area, and the standard daily average and real efficiency has been computed applying previous equations and compared to analyse the results for the five PV panels in Merida city.

Table 2. Potential energy, efficiency and power generated per area results for different PV panels in Merida city

Manufacturer	Model	$P_{mppMEAN}$ (W)	$P_{mpp(STC)}$ (W)	$Area$ (m^2)	P_{sMEAN} (W/m^2)	$P_{s(STC)}$ (W/m^2)	$*\eta_{STC}$ (%)	$*\eta_{MEAN}$ (%)*	$*\eta_{REAL}$ (%)*	Difference η_{REAL}/η_{STC}
Yingli Solar	YL110Wp	40.48	110.25	0.99	40.88	111.36	11.13	9.60	4.08	-63.3%
Blue Carbon	BCT110-12	40.54	110.08	0.85	47.69	129.50	12.95	11.20	4.76	-63.2%
Mitsubishi	MF110EC4	39.38	109.95	0.92	42.80	119.51	11.95	10.05	4.28	-64.2%
Shell	SM110-12P	40.31	109.98	0.86	46.87	127.88	12.78	11.00	4.68	-63.3%
SolarTech	SPM110P	41.00	110.50	0.81	50.61	136.41	13.64	11.88	5.61	-58.8%

* See equation (9) where E_{mean}=425.78 W/m^2 and E_{STC}=1000W/m^2

The potential generation of electricity energy in Merida city has been calculated per day, month and year for each different PV panels to select the best performance and efficiency.

Table 3. Potential of electricity energy in Merida city per day, month and year

Manufacturer	Model	P_{sMEAN} (W/m^2)	$P_{s(STC)}$ (W/m^2)	η_{REAL} (%)*	$*E_{pot\ DAY}$ ($kWhr/m^2$)	$E_{pot\ MONTH}$ ($kWhr/m^2$)	$E_{pot\ YEAR}$ ($kWhr/m^2$)
Yingli Solar	YL110Wp	40.88	111.36	9.60	0.4975	15.17	182.04
Blue Carbon	BCT110-12	47.69	129.50	11.20	0.5803	17.69	212.28
Mitsubishi	MF110EC4	42.80	119.51	10.05	0.5208	15.88	190.56
Shell	SM110-12P	46.87	127.88	11.00	0.5704	17.39	208.68
SolarTech	SPM110P	50.61	136.41	11.88	0.6159	18.78	225.36

*See equation (10) Where Hr_{day}=12.17

For Merida city has been demonstrated that the Solar Tech SPM110P PV panel has the best conditions using the proposed method. At future, if there is some project that requires sizing potential of electricity energy to be produced, for example the home average electrical energy consumption (180kWhr/m^2) per month, applying the proposed method, ten PV panel most be installed to ensure the generation.

4. Conclusion

In this paper has been validated a practical method to estimate the potential of power generation through the PV cell model and the daily average of climatic parameters database such as temperature, solar radiation and daylight hours, for a specific location.

To prove the method a practice case in the Merida city with the five different PV panel, has been applied to estimate the potential electricity generated in a day, month or year.

A difference between the potential of solar radiation versus the potential of electricity generation has been demonstrated, particularly the real efficiency has been lower almost 50% than STC efficiency, therefore this method has been proved for planning generation projects, estimating potential energy and providing certainty to PV systems investment.

The information and the method provided can be applied for different geographical locations and different panels in order to determine the best performance, behaviour and efficiency conditions for electricity energy production from solar energy.

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